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Using the X-FEL to photo-pump X-ray laser transitions in He-like Ne

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ABSTRACT

Nearly four decades ago H-like and He-like resonantly photo-pumped laser schemes were proposed for producing X-ray lasers. However, demonstrating these schemes in the laboratory has proved to be elusive because of the difficulty of finding a strong resonant pump line. With the advent of the X-ray free electron laser (X-FEL) at the SLAC Linac Coherent Light Source (LCLS) we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of resonantly photo-pumped laser schemes. In this paper we use the X-FEL at 1174 eV to photo-pump the singly excited 1s2p state of He-like Ne to the doubly excited 2p3p state and model gain on the 2p3p-2p2s transition at 175 eV and the 2p3p-1s3p transition at 1017 eV. One motivation for studying this scheme is to explore possible quenching of the gain due to strong non-linear coupling effects from the intense X-FEL beam We compare this scheme with photo-pumping the He-like Ne ground state to the 1s3p singly excited state followed by lasing on the 3p-2s and 3d-2p transitions at 158 and 151 eV. Experiments are being planned at LCLS to study these laser processes and coherent quantum effects.

Keywords: X-ray laser, X-FEL; Photo-pumping

1. INTRODUCTION

From the earliest days of lasers, resonantly photo-pumped laser schemes using H-like and He-like ions were proposed for producing X-ray lasers [1]. However, demonstrating these schemes in the laboratory has proved to be elusive. One challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. Given a good resonance, a second challenge has been to create both the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the advent of the X-FEL at LCLS [2] we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of resonantly photo-pumped laser schemes. In previous papers we modeled the Na-pumped Ne X-ray laser scheme that was proposed and studied many years ago by replacing the Na He-α pump line at 1127 eV that pumped the Ne He-γ line with the X-FEL at LCLS. We predicted gain [3] greater than 400 cm^{-1} on the 4f – 3d transition at 231 Å that is orders of magnitude larger than the gains predicted [4] two decades ago using the Saturn pulsed power machine at Sandia National Laboratory to create the Na pump line.

In this paper we use the X-FEL at 1174 eV to resonantly photo-pump the singly excited 1s2p $^1P_2$ state of He-like Ne to the doubly excited 2p3p $^1D_3$ state and model gain on the 2p3p $^1D_3$ - 2p2s $^1P_2$ transition estimated at 175 eV and the 2p3p $^1D_3$ - 1s3p $^1P_2$ transition estimated at 1017 eV. We compare this with photo-pumping the He-like Ne $1s^2$ $^1S_0$ ground state to the 1s3p $^1P_1$ singly excited state followed by lasing on the 1s3p $^1P_1$ – 1s2s $^1S_0$ and 1s3d $^1D_2$ – 1s2p $^1P_1$

transitions estimated at 158 and 151 eV. Normally one would expect much higher gain from resonantly photo-pumping the ground state of He-like Ne but in the case of the X-FEL this is not the case because we are able to create large populations in singly excited states. Experiments are being planned at LCLS to study these laser processes and coherent quantum effects.

2. CHARACTERISTICS OF THE LCLS X-FEL

For modeling the resonantly photo-pumped He-like Ne schemes in this paper we looked at the characteristics [5] of X-FEL at the LCLS facility laser. The basic features of the X-FEL is that it can produce a tunable X-ray source that extend from 800 to 8500 eV. It operates at a 120 Hz repetition rate with approximate output of 10^{12} photons per pulse. The beam has a spectral bandwidth of 0.1% of the fundamental, a pulse duration of 100 - 200 fs, and an unfocused spot size of 400 μm square and a focused spot size of 1 μm. The beam can be rapidly tuned over 3% of the fundamental energy by adjusting the electron beam energy. In order to photo-ionize the Ne gas down to He-like before photo-pumping the resonant transitions we need as much intensity as possible so we assume a 100-fsec pulse duration and the 1-μm focused spot size. Using these numbers gives a spectral intensity $I_\varepsilon = 1.6 \times 10^{17}$ W / (eV cm^2). We can calculate the line strength of the X-FEL beam in photons per mode $n_\varepsilon = 1.579 \times 10^{-5} I_\varepsilon / \varepsilon^3$ where ε is the photon energy in eV. Looking at some typical photon energies $n_\varepsilon = 1765$ at 1127 eV and drops to 9.45 at 6442 eV for the focused beam. For a photo-pumped laser scheme the beam strength in photons per mode is approximately the same as the maximum fractional population divided by the statistical weight of the level being pumped.

The starting condition for all the modeling is an ion density of 10^{18} cm^{-3} for the Ne plasma and a temperature of 1 eV. The CRETIN code [6] in combination with a detailed atomic model and an X-ray source representing the X-FEL is used to model the kinetics in one dimension (1D) to scope out the potential gain that can be achieved in experiments.

3. HE-LIKE NE X-RAY LASER SCHEME

First let us consider resonantly photo-pumping the He-like Ne ground state to the 1s3p singly excited state followed by lasing on the 3p-2s and 3d-2p transitions at 158 and 151 eV as shown in Fig. 1. To accomplish this one uses the LCLS X-FEL at an energy of 1074 eV. The X-FEL is used to photo-ionize the neutral Ne gas down to He-like Ne and then to photo-pump the $1s^2\ ^1S_0$ ground state to the $1s3p\ ^1P_1$ upper laser state. Table 1 shows the K-edge for photo-ionization used in the atomic model. Starting with neutral Ne gas the 1074 eV X-ray will first photo-ionize a K shell electron and create a highly ionized F-like ion that will predominately auger decay to the O-like ground state. This will be followed by another photo-ionization and auger decay until Ne reaches Be-like Ne. At this point the X-FEL is below the K-edge energy of 1099 eV but the X-FEL can easily photo-ionize the L-shell electrons and other singly excited states and reach He-like Ne. While the K-shell photo-ionization rate is about 0.15 fsec^{-1} the L-shell photo-ionization rate is an order of magnitude slower. This is reflected in Fig. 2 that shows the ionization fraction versus time for each ionization stage of Ne. The X-FEL intensity peaks at a time of 200 fs with a 100 fs FWHM. One observes that the plasma has about 15% He-like (solid curve with solid circles) and 40% Li-like ions (dashed line with no markers). The electron temperature of the plasma quickly reaches 200 eV while the ion temperature stays near the initial room temperature given the short time scale. Figure 3 shows the gain versus time of the one strong gain line on the 3p-2s transition that we estimate to be at a photon energy of 158 eV. Peak gain is about 80 cm^{-1}. The upper laser state of this line is directly populated by resonantly photo-pumping by the 1074 eV X-FEL. The second laser line at 151 eV on the 3d-2p transition at 151 eV requires collisional excitations to transfer population from the 3p to 3d level and therefore has much weaker gain that takes much longer to develop.

Table 1	
Ionization stage	K-edge (eV)
Neutral Ne-like (Ne I)	867
F-like (Ne II)	892
O-like (Ne III)	923
N-like (Ne IV)	958
C-like (Ne V)	1002
B-like (Ne VI)	1047
Be-like (Ne VII)	1099
Li-like (Ne VIII)	1143
He-like (Ne IX)	1194
H-like (Ne X)	1362

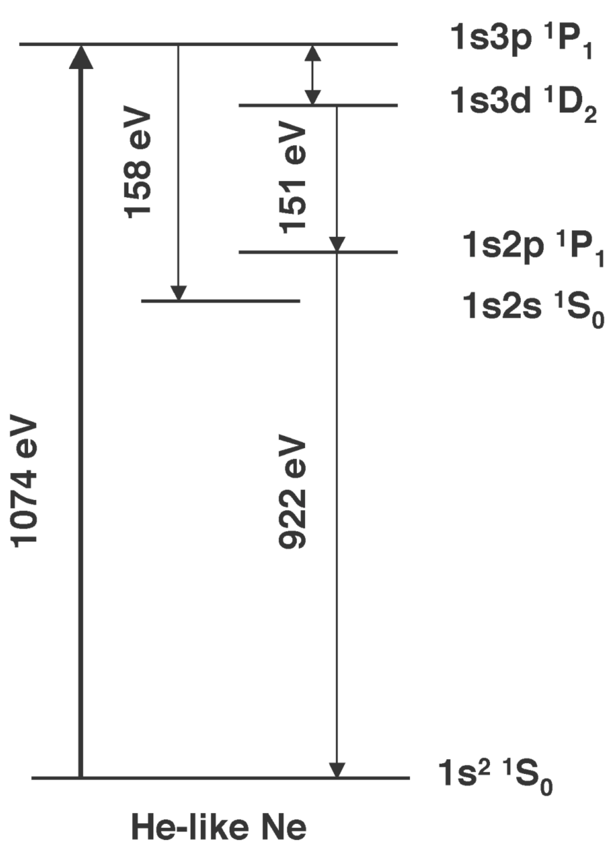

Fig. 1. Energy level diagram for the 1074 eV X-FEL resonantly photo-pumping the 1s-3p transition from the He-like ground state and creating gain on the 3p-2s and 3d-2p lines estimated at 158 and 151 eV.

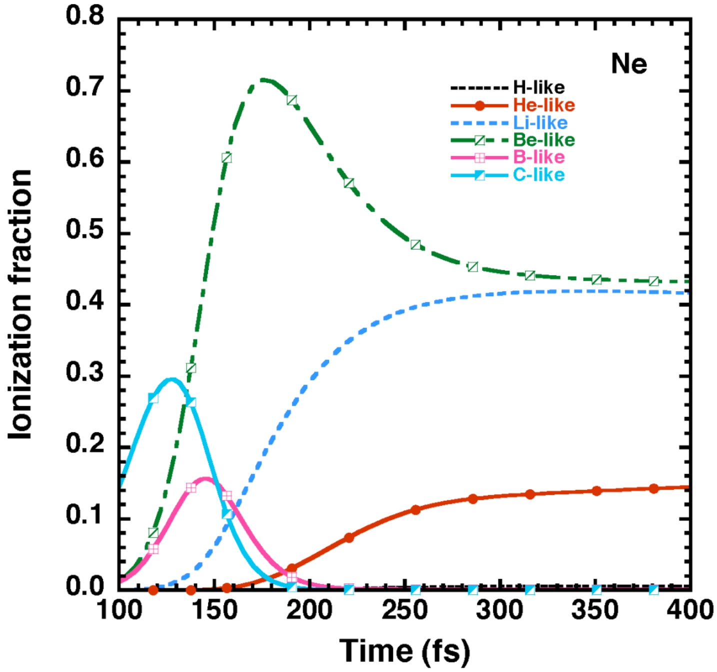

Fig. 2. Ionization fraction versus time for a Ne plasma driven by a 1074 eV X-FEL. The X-FEL peaks at 200 fs on this time scale with a 100 fs FWHM duration. The He-like fraction quickly reaches 15% as shown by the solid line with solid circles.

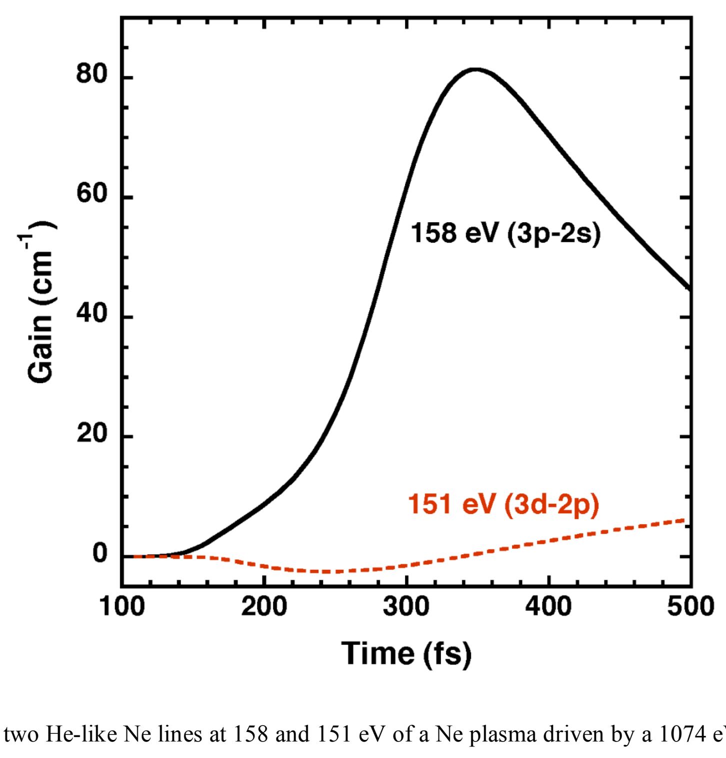

Fig. 3. Gain versus time for two He-like Ne lines at 158 and 151 eV of a Ne plasma driven by a 1074 eV X-FEL. The X-FEL peaks at 200 fs on this time scale with a 100 fs FWHM duration.

Next lets consider using the X-FEL at 1174 eV to resonantly photo-pump the singly excited 1s2p $^1P_2$ state of He-like Ne to the doubly excited 2p3p $^1D_3$ state and model gain on the 2p3p-2p2s transition at 175 eV and the 2p3p-1s3p transition at 1017 eV. The transitions are shown in Fig. 4 with the calculated energies. For this case, looking at Table 1, the X-FEL has enough energy to photo-ionize the K-shell electrons all the way down to He-like Ne. This is reflected in Fig. 5 that shows the ionization fraction versus time for the different ionization stages of Ne. The solid curve with solid circle markers shows that we produce almost 55% He-like Ne and even have enough energy to produce 10% H-like Ne. Again the electron temperature quickly reaches slightly over 200 eV. In terms of the kinetics almost 4% of the population is in the 1s2p state that is locked into equilibrium with the 2p3p upper laser state by the X-FEL. For this case both laser transitions have the same upper laser state. Figure 6 shows the gain versus time for both transitions. The 3p-2s line estimated at 175 eV has peak gain of about 70 cm^{-1} and lasts for hundreds of fsecs. For this transition the lower laser state is essentially empty. For the 2p-1s line estimated at 1017 eV the peak gain is about 25 cm^{-1} and lasts for about a hundred fsecs. The gain is shorted lived because in this case the 1s3p lower laser state does get populated rapidly and cuts off the inversion by 300 fsec. One can see that for the 175 eV line the gain is very similar to the previous case where we resonantly photo-pump the He-like ground state. By resonantly photo-pumping the singly excited state instead of the ground state we have this second high-energy line with high gain. Typical targets used in experiments are 0.5 – 1.0 cm long so we could expect strong amplification and near saturation for both lines.

4. CONCLUSIONS

Since the early days of laser research H-like and He-like resonantly photo-pumped laser schemes have been proposed for producing X-ray lasers. However, demonstrating these schemes in the laboratory has proved to be elusive. One challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. Given a good resonance, a second challenge has been to create both the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the advent of the X-FEL at LCLS we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes.

In this paper we use the X-FEL at 1174 eV to photo-pump the singly excited 1s2p state of He-like Ne to the doubly excited 2p3p state and model gain on the 2p3p-2p2s transition at 175 eV and the 2p3p-1s3p transition at 1017 eV. We compare this with photo-pumping the He-like Ne $1s^2$ $^1S_0$ ground state to the 1s3p $^1P_1$ singly excited state followed by lasing on the 3p-2s and 3d-2p transitions at 158 and 151 eV. We predict peak gains of 70 – 80 cm^{-1} for the 175 and 158 eV lines and 25 cm^{-1} for the 1017 eV line for a Ne plasma with an ion density of 10^{18} cm^{-3}. Normally one would expect much higher gain from photo-pumping the ground state of He-like Ne but in the case of the X-FEL this is not the case because we are able to create large populations in singly excited states. Experiments are being planned at LCLS to study these laser processes and coherent quantum effects. In addition to looking for gain and lasing the X-FEL can also be used to study the kinetics of these laser systems by observing the dynamic evolution of the fluorescent lines.

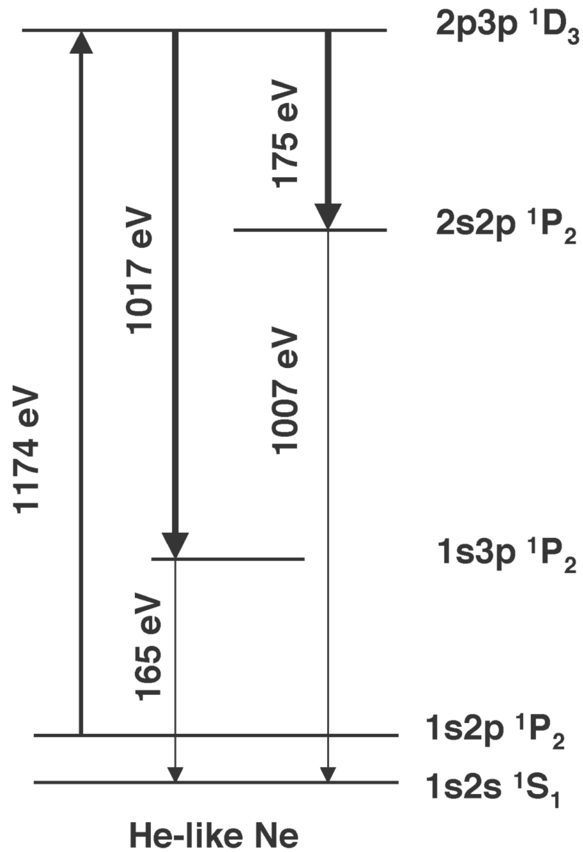

Fig. 4. Energy level diagram for the 1174 eV X-FEL resonantly photo-pumping the 1s-3p transition from the 1s2p $^1P_2$ singly excited state and creating gain on the 3p-2s and 2p-1s lines estimated at 175 and 1017 eV.

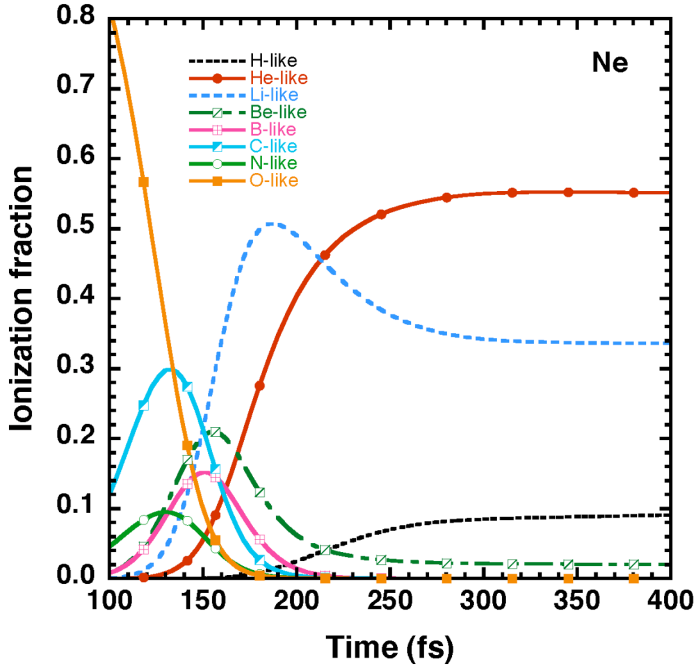

Fig. 5. Ionization fraction versus time for a Ne plasma driven by a 1074 eV X-FEL. The X-FEL peaks at 200 fs on this time scale with a 100 fs FWHM duration. The He-like fraction quickly reaches 15% as shown by the solid line with solid circles.

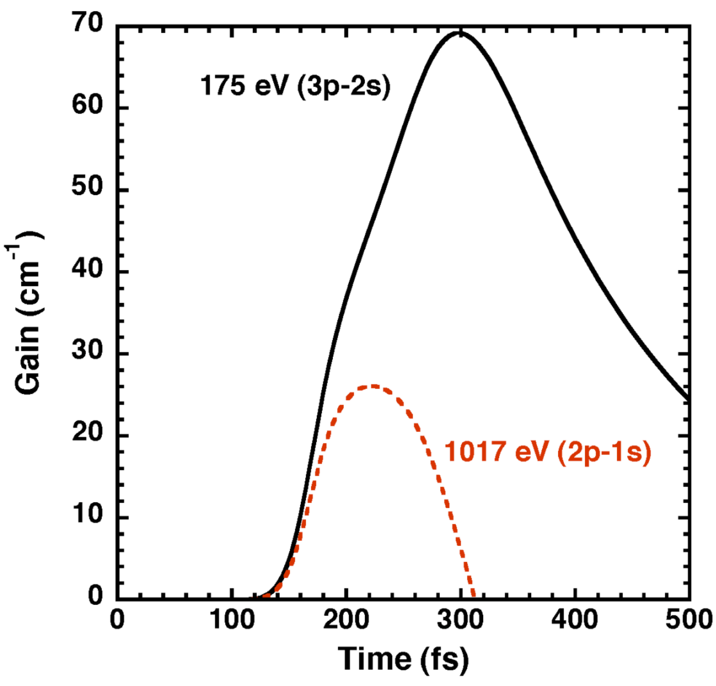

Fig. 6. Gain versus time for two He-like Ne lines at 158 and 151 eV of a Ne plasma driven by a 1074 eV X-FEL. The X-FEL peaks at 200 fs on this time scale with a 100 fs FWHM duration.

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